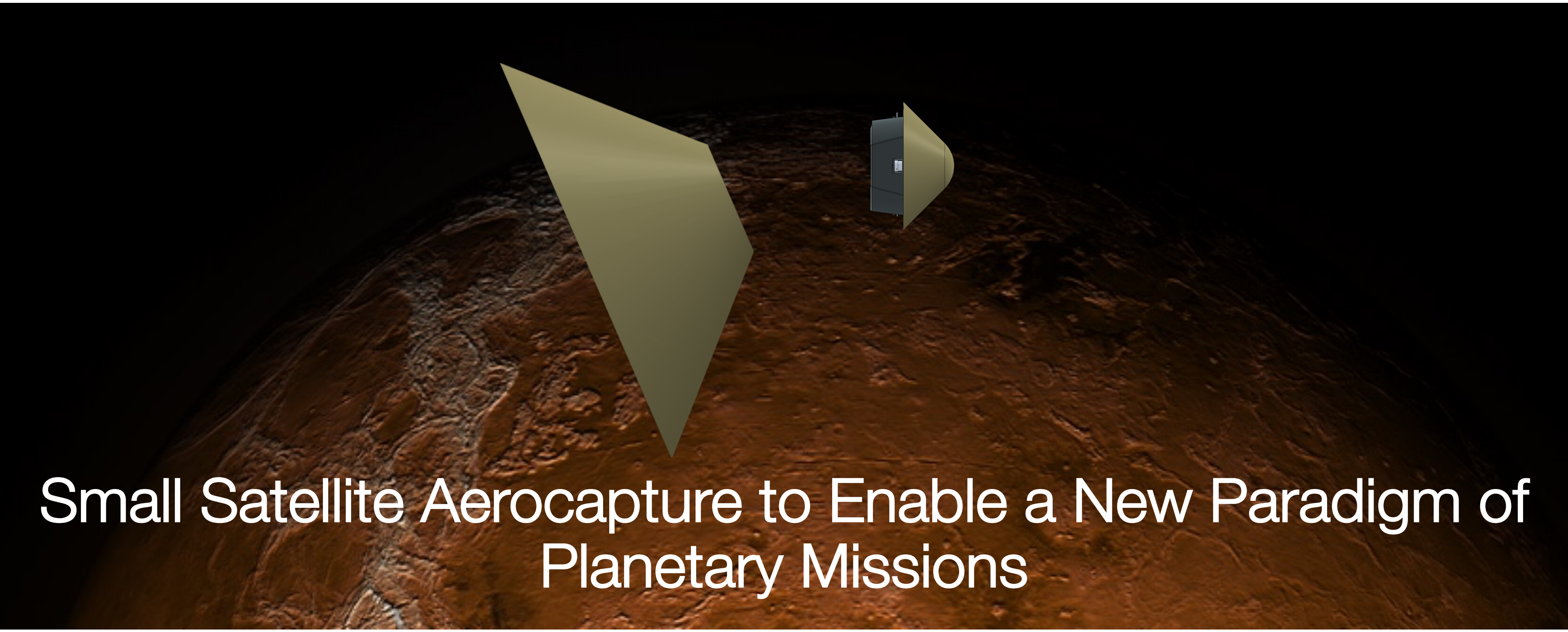

Small Satellite Aerocapture to Enable a New Paradigm of Planetary Missions

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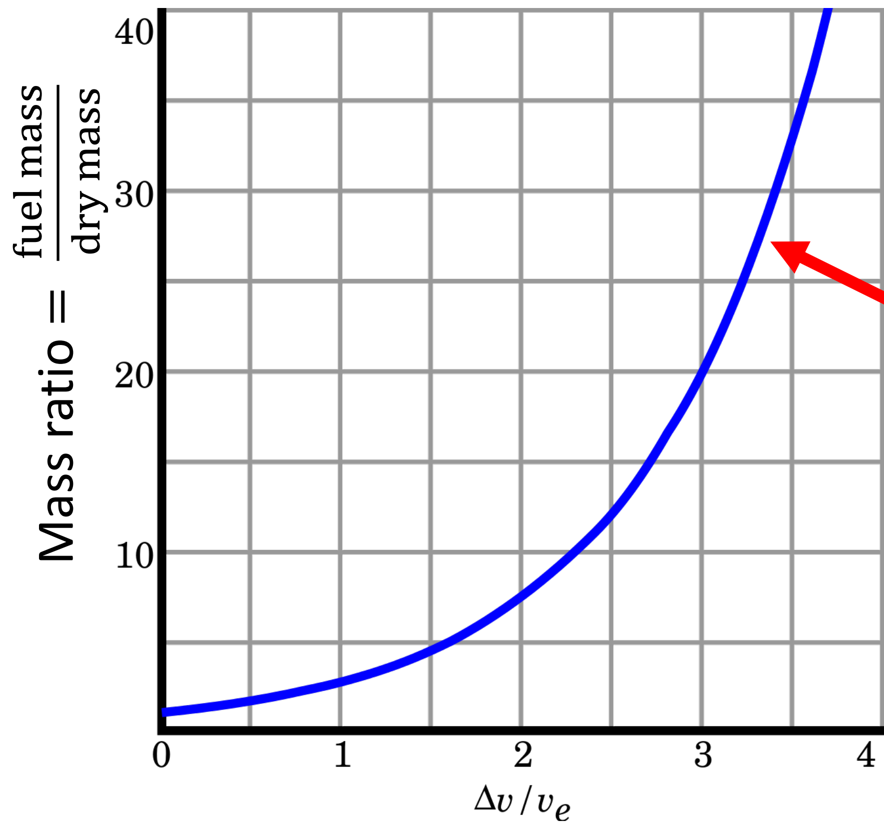
University of Colorado Boulder

March 6, 2019

The Rocket Equation

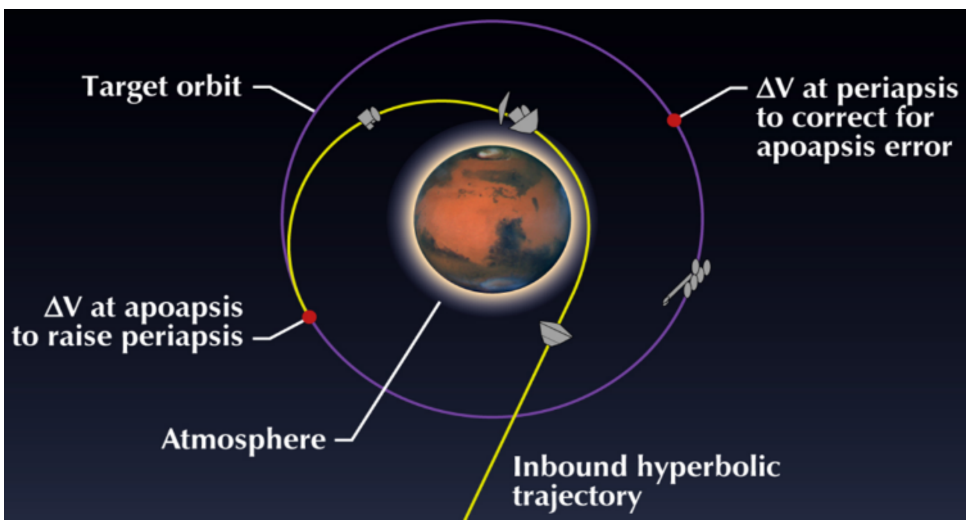
$$\Delta v = v_e \ln \frac{m_o}{m_f}$$



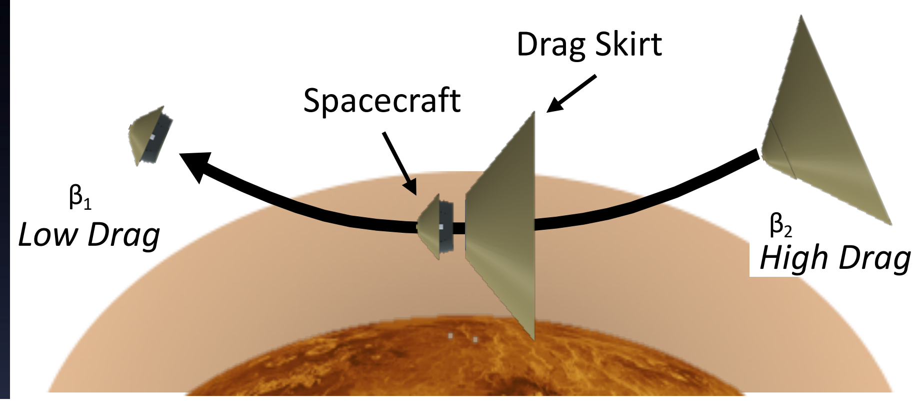
Large changes of velocity require large amounts of propellant! What if we could change this?

Aerocapture Overview

- Aerocapture is a method to enter orbit around a body with an atmosphere
  - The spacecraft approaches the body on a hyperbolic trajectory and sheds all of the velocity needed to enter orbit due to drag
- Drag modulation flight control can be used to target a specific orbit
  - Timing of a single-event jettison of a drag skirt is used to target a specific science orbit

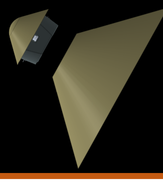


Aerocapture uses the drag from a single pass through the atmosphere to enter orbit, rather than a large burn from a propulsion system

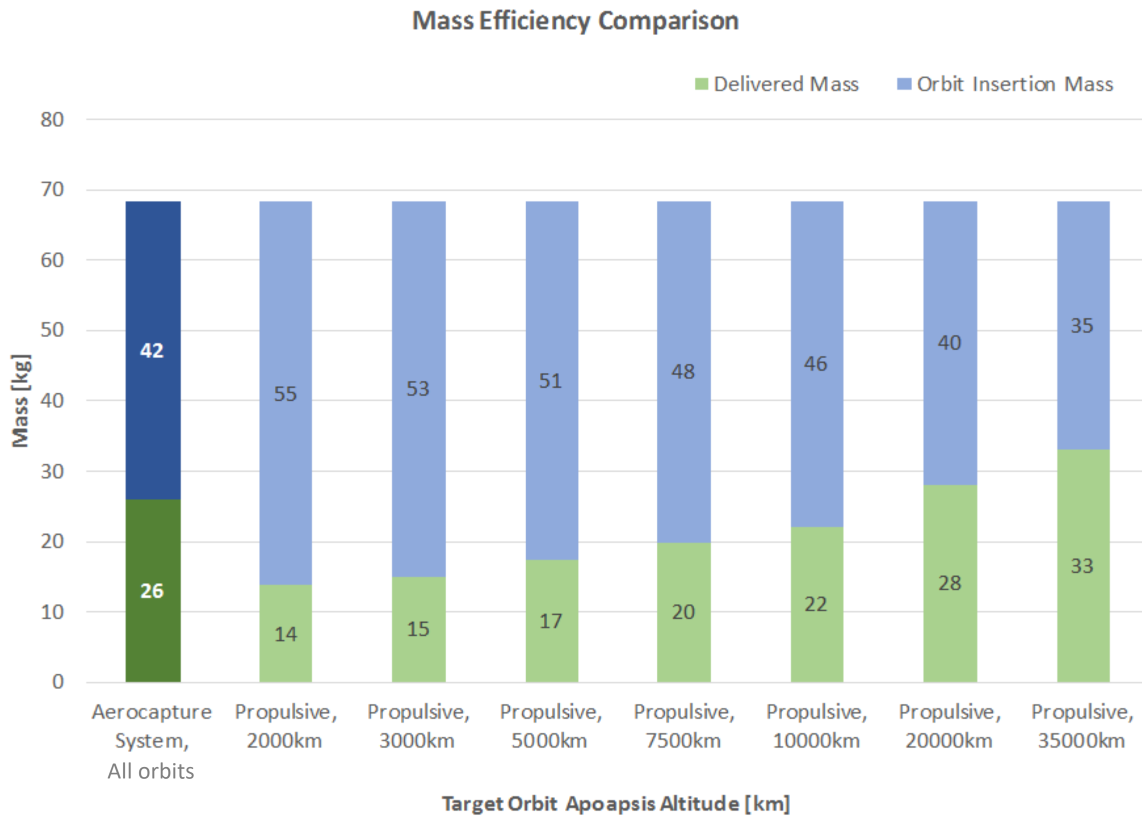


By modulating the time that the drag skirt is jettisoned from the spacecraft a specific orbit can be targeted

Aerocapture Mission Benefits



- Provide orbit insertion capability for mass and/or volume constrained small satellites
- Enable rapid transport throughout the solar system
- Increase mass efficiency to orbit

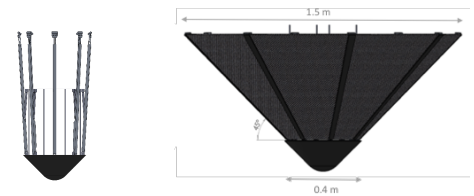


Aerocapture can deliver 50-85% more useful mass for orbits ranging from 5000 km down to 2000 km at Venus

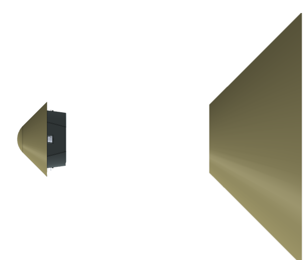
Aerocapture Mission Trade Space

- Potential Destinations:
  - Venus
  - Earth
  - Mars
  - Titan
  - Ice Giants
- Vehicle Options:
  - Mechanical deployable drag skirt
  - Rigid drag skirt
- Delivery Schemes:
  - Dedicated launch & cruise
  - Delivery by host spacecraft

Mechanical deployable drag skirt



Rigid drag skirt



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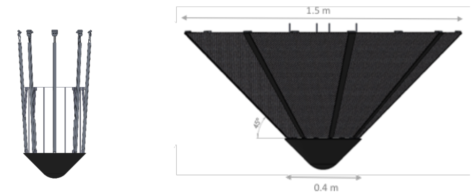
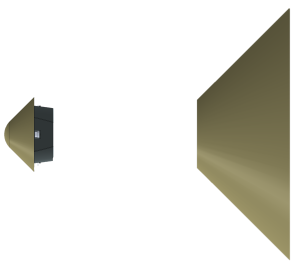
Mechanical deployable drag skirt



Rigid drag skirt



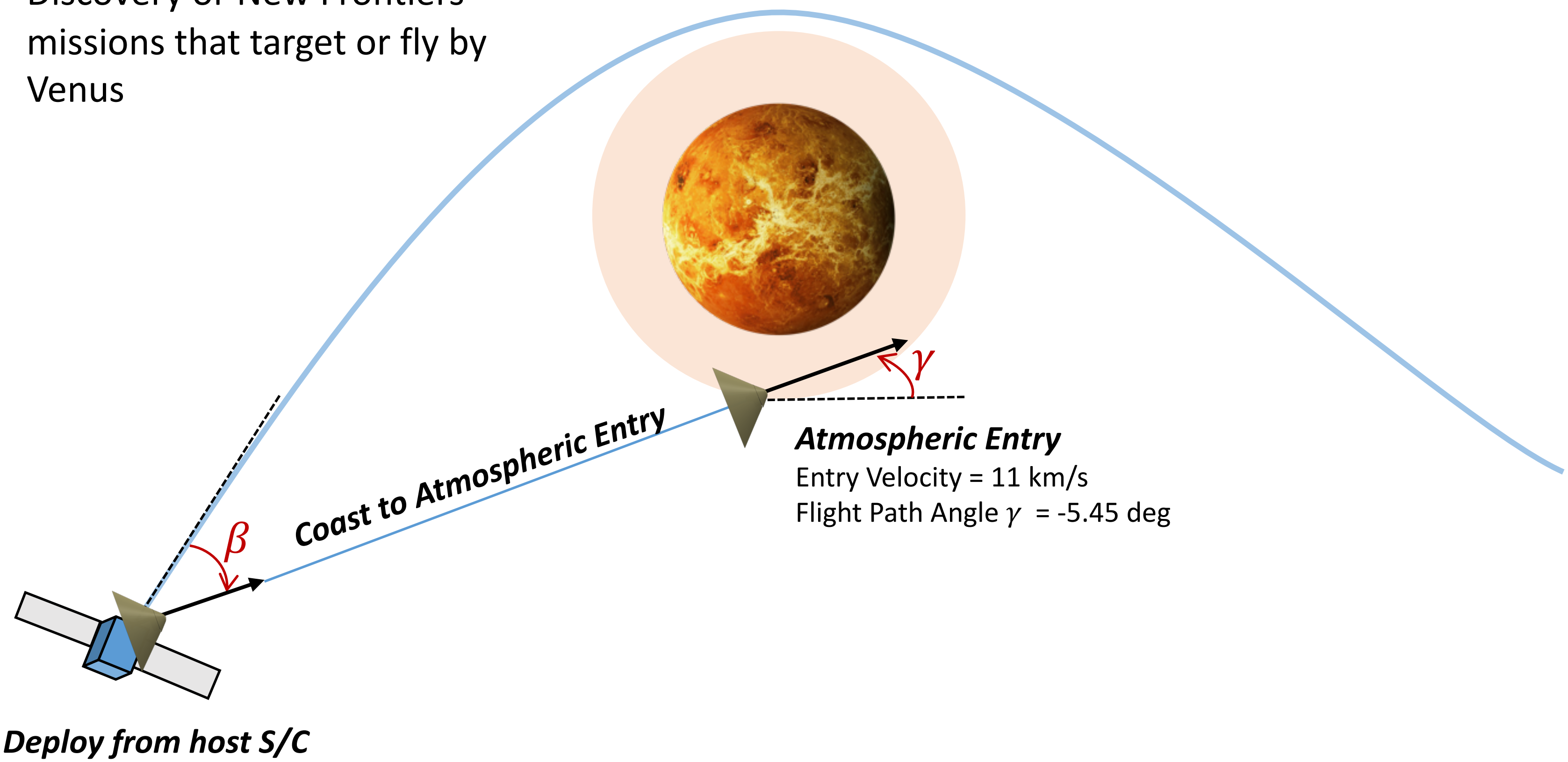
Initial Focus:

Chose Venus to bound the technology's capability. Can scale to "easier" destinations.
Chose rigid drag skirt and host spacecraft delivery to minimize system complexity.

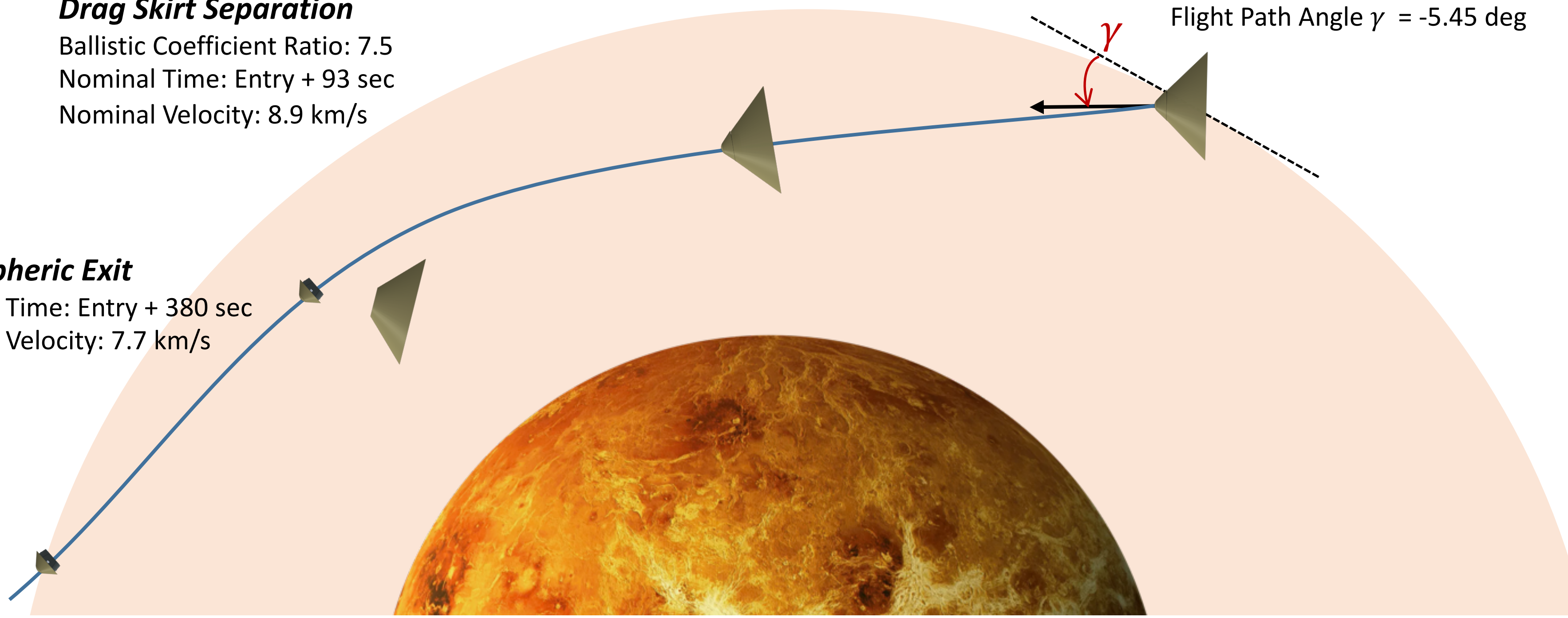
ConOps: Exo-Atmospheric

Potential Hosts:

- Dedicated carrier spacecraft
- Discovery or New Frontiers missions that target or fly by Venus



ConOps: Atmospheric



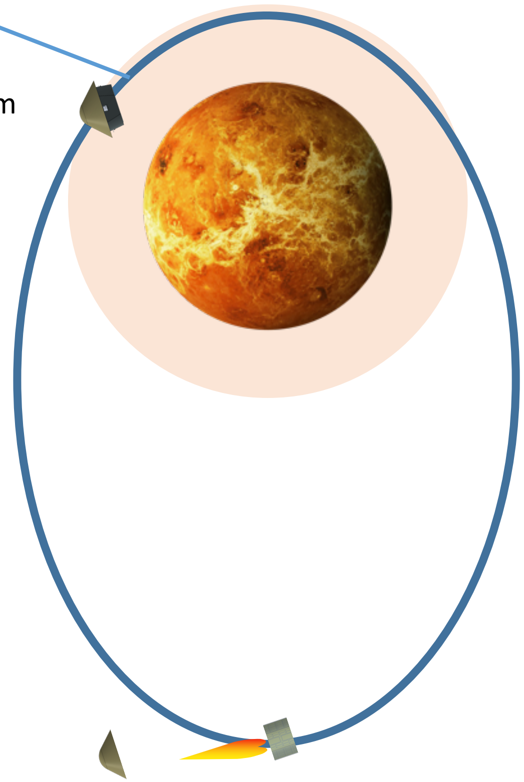
ConOps: Post-Aerocapture

Initial Orbit

Periapsis: 100 km

Apoapsis: 2000 km

Period: 1.83 hr



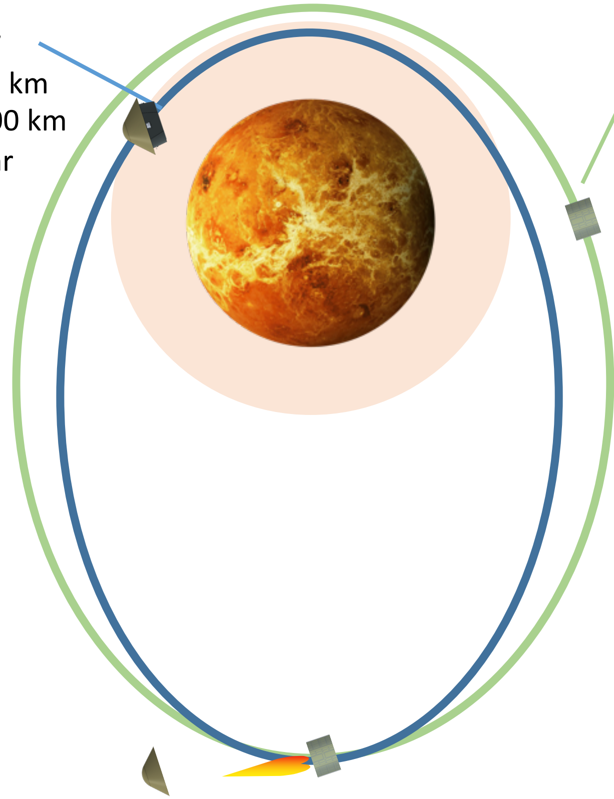
Drop Heat Shield +
Periapsis Raise Maneuver

Nominal Time: Atm. Exit + ½ Period

Trigger: Timer

ConOps: Post-Aerocapture

Initial Orbit
Periapsis: 100 km
Apoapsis: 2000 km
Period: 1.83 hr

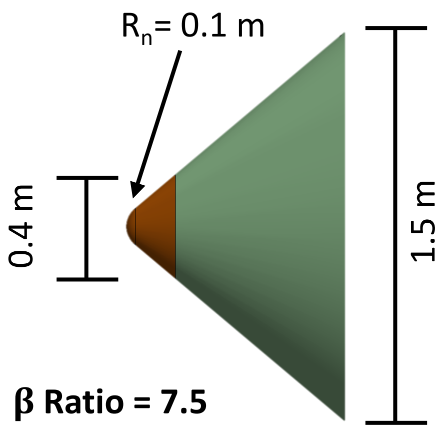


Final Orbit
Periapsis: 200 km
Apoapsis: 2000 km
Period: 1.85 hr

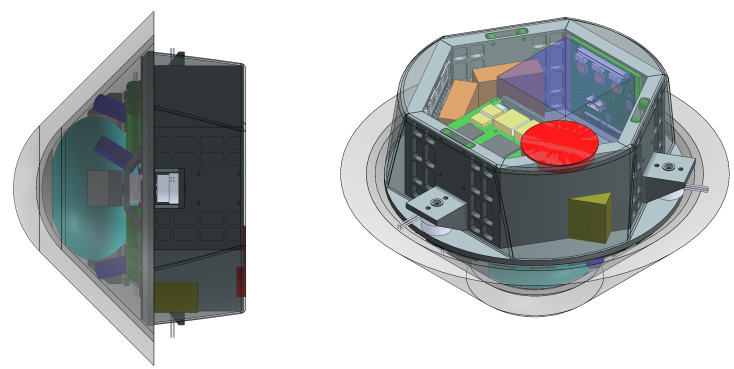
Drop Heat Shield +
Periapsis Raise Maneuver
Nominal Time: Atm. Exit + 55 minutes
Trigger: Timer

Representative Flight System

Pre-Jettison Configuration



Delivered Flight System



Total Margined Mass = 69kg

- Science Payload
  - ~2U available volume
- Telecom
  - IRIS X-Band Radio
  - X-Band Patch Antenna
  - X-Band Circular Patch Array HGA
- ACS
  - BCT Star Tracker, Sun Sensors (x4), and Control Electronics
  - BCT Reaction Wheels (x3)
  - Sensonor IMU
- C&DH
  - JPL Sphinx Board
  - Pyro Control Board

- Thermal
  - Kapton Film Heaters
  - MLI
  - Radiator Panels
- Power
  - Solar Arrays
  - Control electronics
  - 18650 Li-ion batteries (x11) (~180 Wh)
- Propulsion *(~70 m/s delta-V)*
  - 0.5 N Monoprop Thrusters (x4)
- Mechanical
  - Structure, TPS, Rails, Rollers, Separation Hardware

Key Challenges Addressed

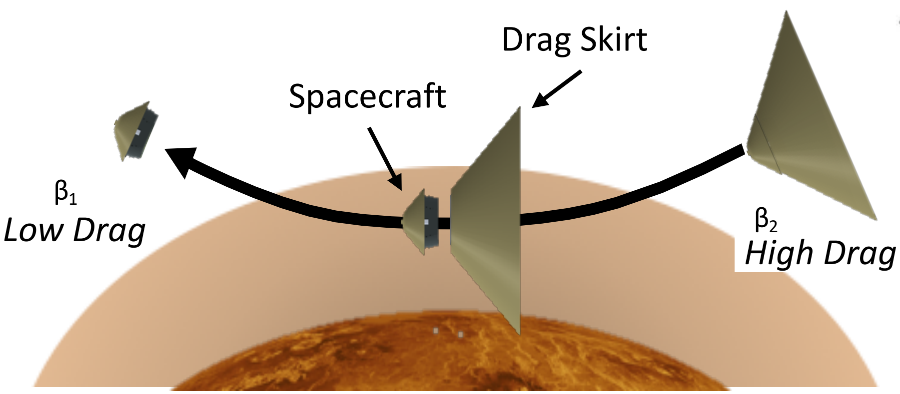
- In 2018, we focused on addressing three key technical challenges:
  1. Orbit Targeting Accuracy
     - Understanding how well the system can target a specific orbit in the presence of navigation and atmospheric uncertainties
  2. Aeroheating and Thermal Protection Systems (TPS)
     - Understanding the aeroheating environment that the vehicle will be subjected to and what TPS is needed
  3. Drag Skirt Re-contact Risk and Vehicle Stability
     - Assessing the risk of recontact of the drag skirt during the jettison event and potential effects on the vehicle's stability

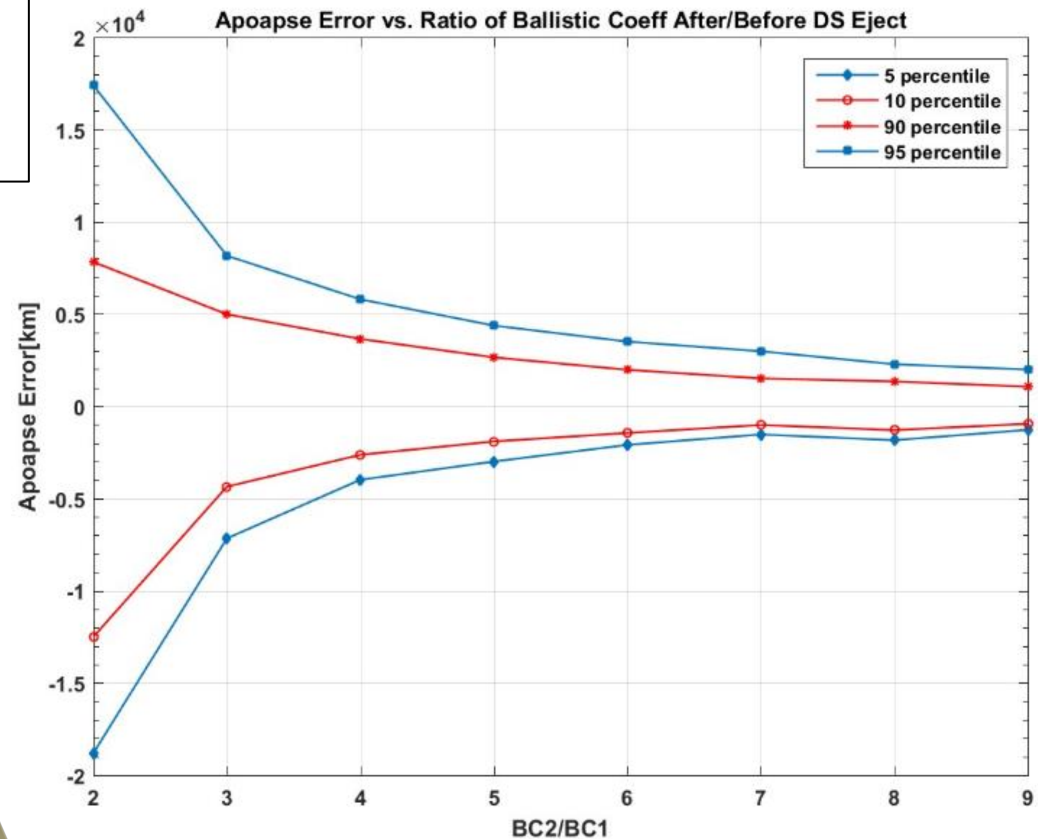
Orbit Targeting: How Much Control is Needed?

3DOF Monte Carlo analysis in JPL's DSENDS trajectory tool used to assess orbit targeting accuracy

Why is a form of control needed?

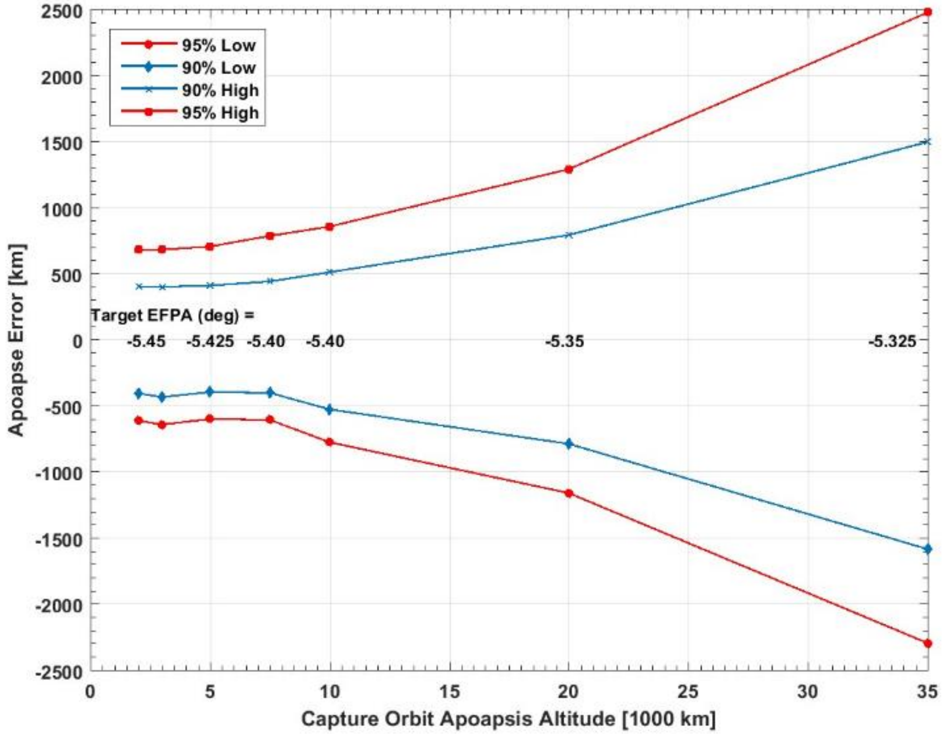
- The plot below shows the error in orbit apoapsis for different ballistic coefficient ratios
- When the ratio approaches 1 (no drag skirt jettison event) errors in orbit targeting increase to unacceptable levels

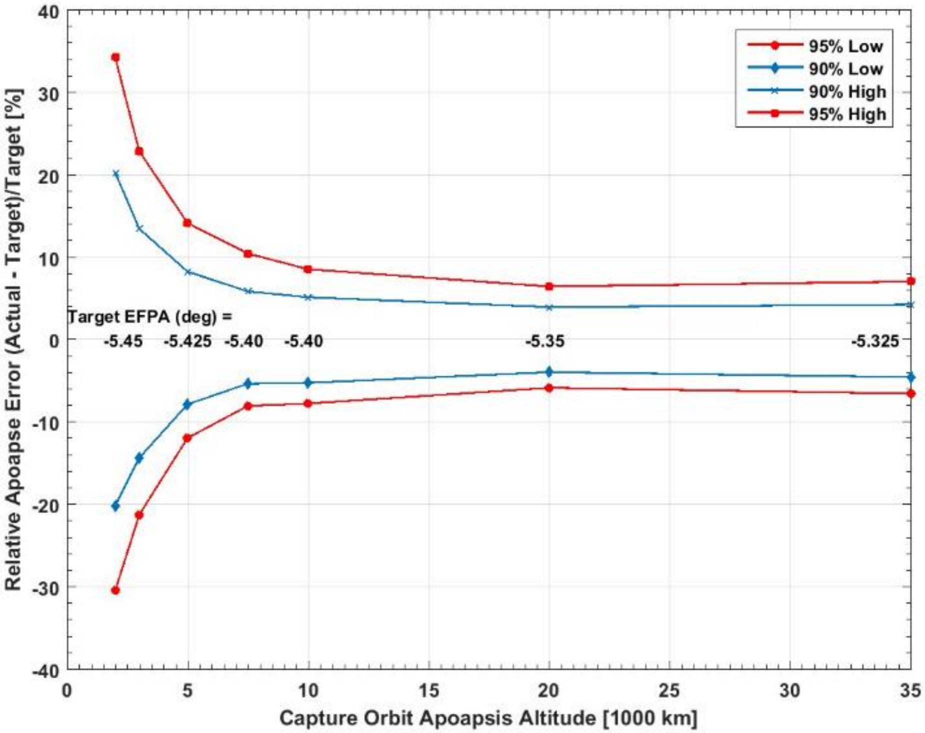




Orbit Targeting: Effects of Targeting Different Orbits

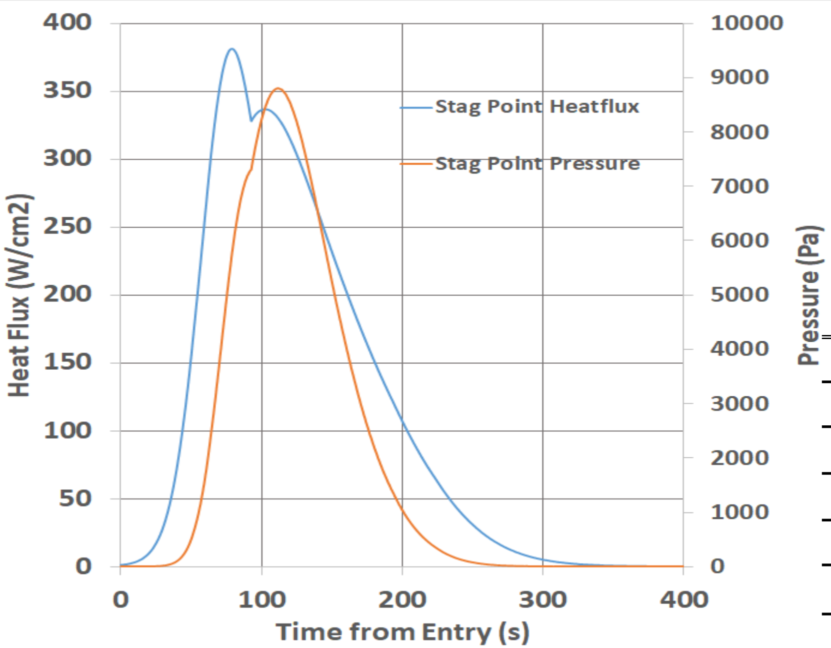
- The aerocapture system can target a number of different orbits
  - Shown below are apoapsis altitudes from 2,000 km to 35,000 km at Venus
- As target orbit apoapsis increases, the expected apoapsis error increases
- However, the relative apoapsis error stabilizes at ~5%, which is similar to the errors with large propulsive orbit insertions



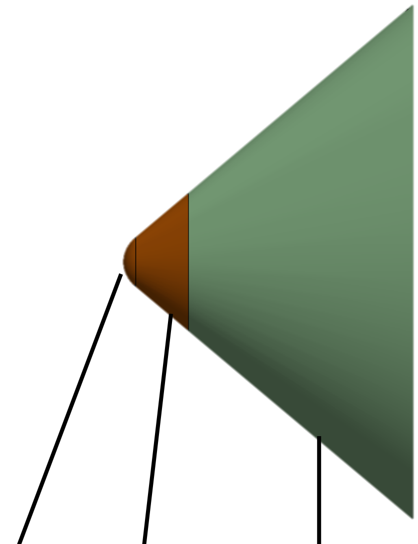


Aeroheating & TPS: Sizing Analysis

Heating environments were developed using the NASA Ames 3-DOF simulation code TRAJ



Stagnation point heating and pressure during the aerocapture maneuver



	Nose	Flank (est)	Skirt (est)
Peak heat flux (W/cm²)	383.30	191.65	191.65
Peak Heat Load (J/cm²)	45179	22590	3840
Peak Pressure (Pa)	8800	4400	3650
C-PICA thickness (cm)	2.58	1.88	0.72
PICA thickness (cm)	4.125	3.51	1.11
C-PICA mass (kg)	0.13	0.80	4.56
PICA mass (kg)	0.20	1.45	6.83

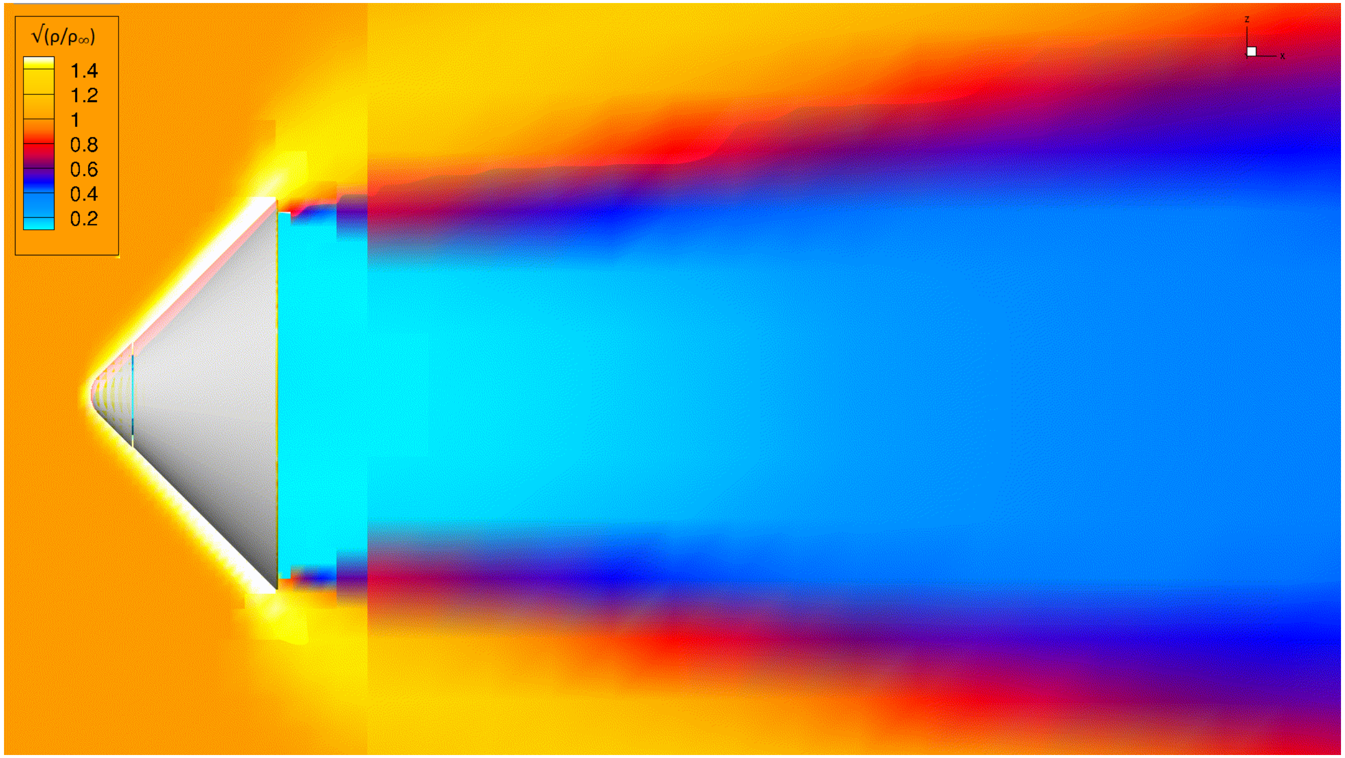
Total heat-shield only TPS mass for pre-and post-jettisoned bodies combined:

C-PICA 5.49 kg (Un-margined engineering estimate, reference design carries double)

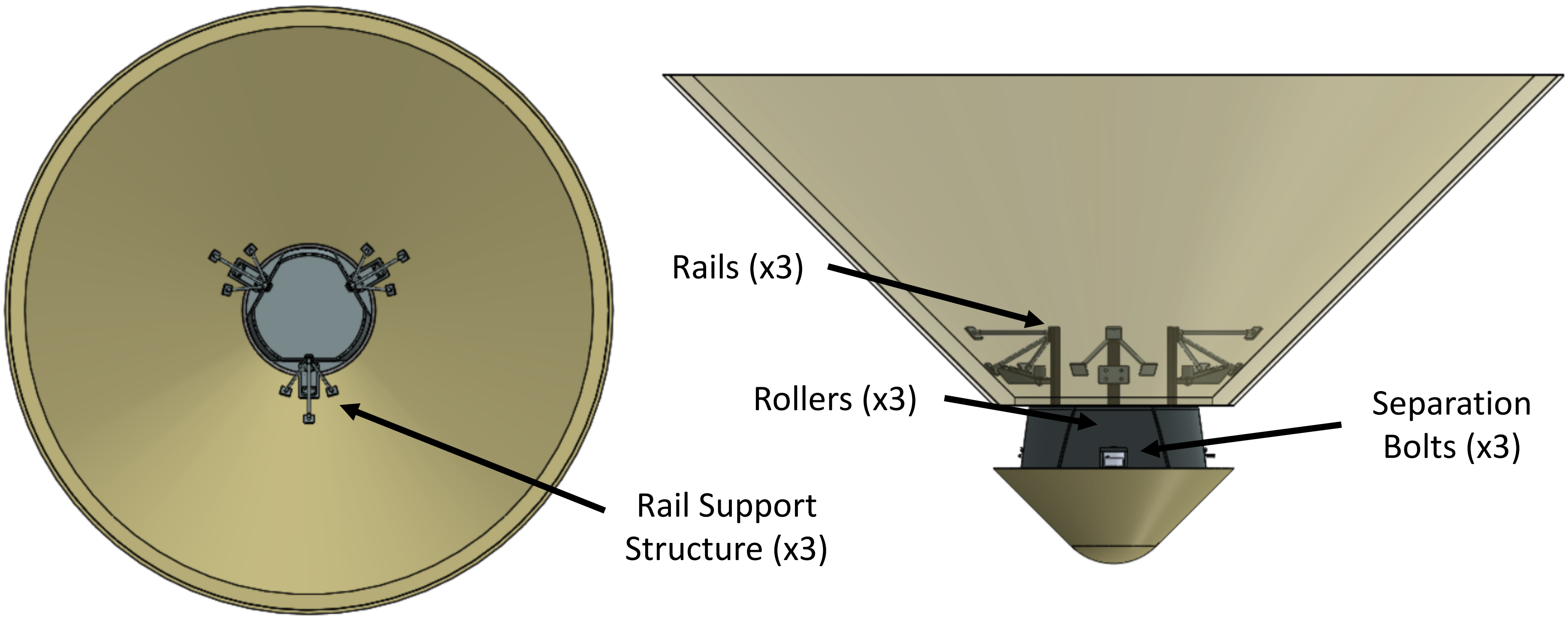
PICA 8.48 kg (Un-margined engineering estimate, reference design carries double)

Re-contact & Stability: CFD

- CFD simulations in Cart3D conducted by CU Boulder
- Dynamic simulations indicate that drag skirt jettison is expected to occur in ~45 ms at Mach = 40
- No drag skirt recontact with spacecraft at angle of attack up to 5 degrees



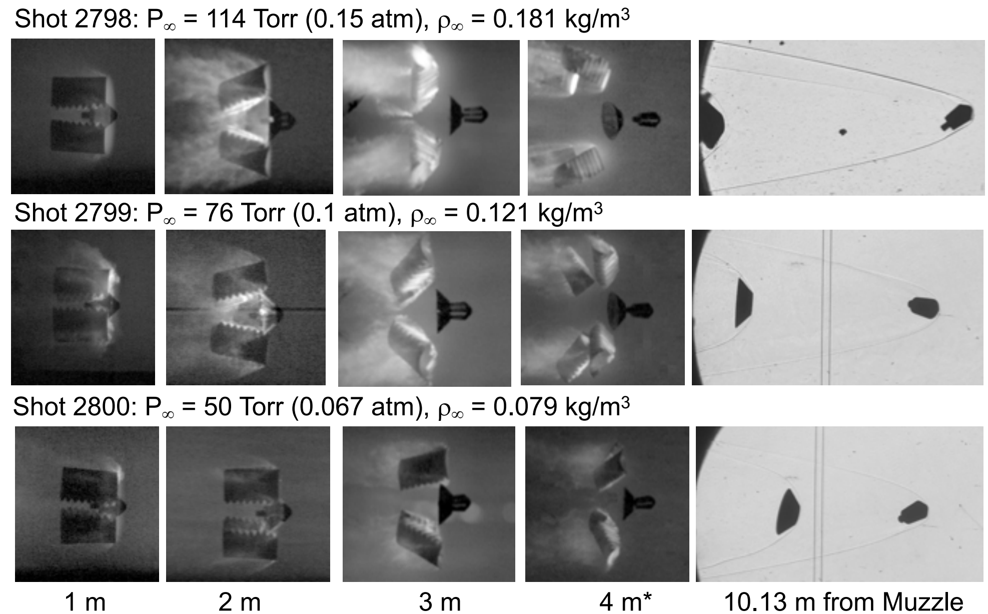
Re-contact & Stability: Rail Design

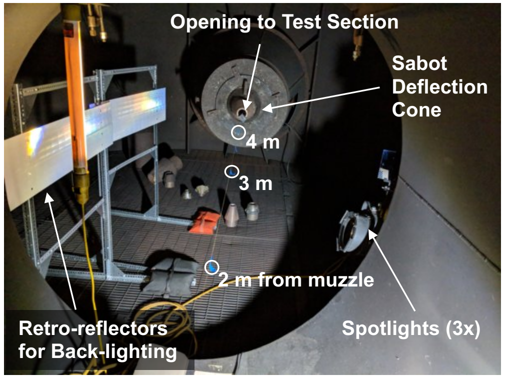


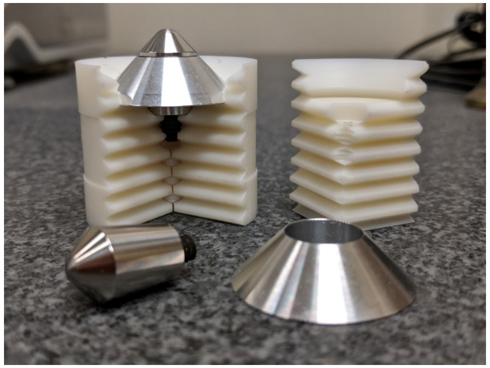
- MSL-inspired rail & roller design reduces drag skirt re-contact risk further by ensuring smooth jettison event
- 3 separation bolts fire when triggered by the flight computer

Re-contact & Stability: Ballistic Range Testing

- Ballistic range at NASA Ames has been modified to image the drag skirt separation event
- Several exploratory test shots were performed in 2018
- Multiple ballistic range shots with representative flight system subscale models planned for this year







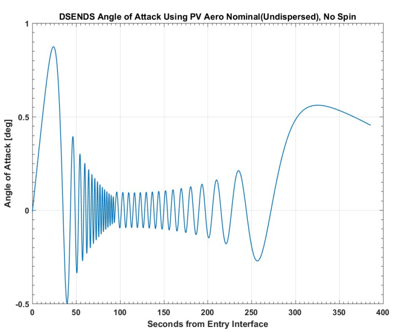
Conclusions and Future Work

This initiative has addressed the following key challenges for drag modulation aerocapture at Venus:

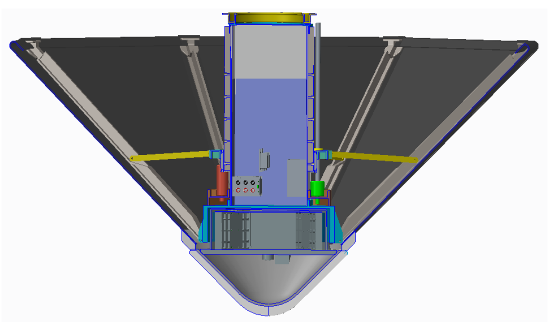
1. Orbit Targeting Accuracy ✓
   - 3-DOF Monte Carlo simulations of the aerocapture maneuver
2. Aeroheating and Thermal Protection Systems (TPS) ✓
   - Preliminary heating and TPS sizing analysis using TRAJ
3. Drag Skirt Re-contact Risk and Vehicle Stability ✓
   - Dynamic CFD simulations with CART3D, rail design, ballistic range testing

The study team is actively continuing work, including:

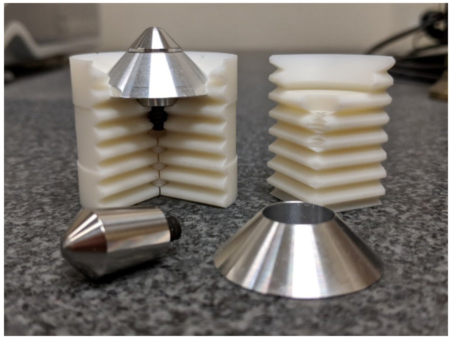
6DOF Trajectory Simulation



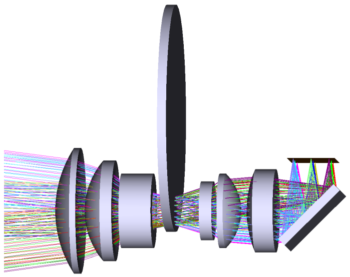
ADEPT drag skirt design



Final Ballistic Range Tests



Investigating Potential Science Missions

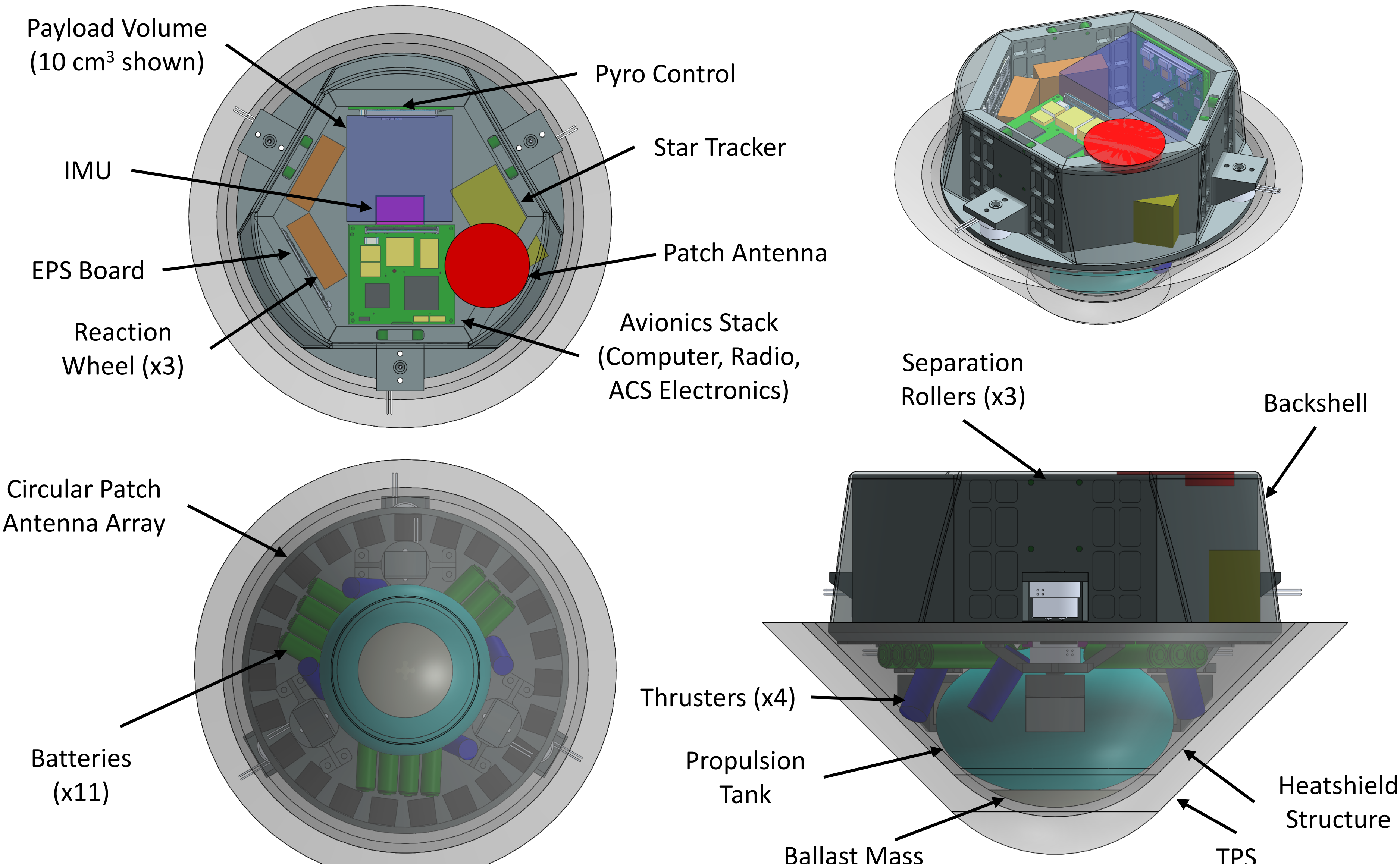


Thank you!

Questions?

Backup

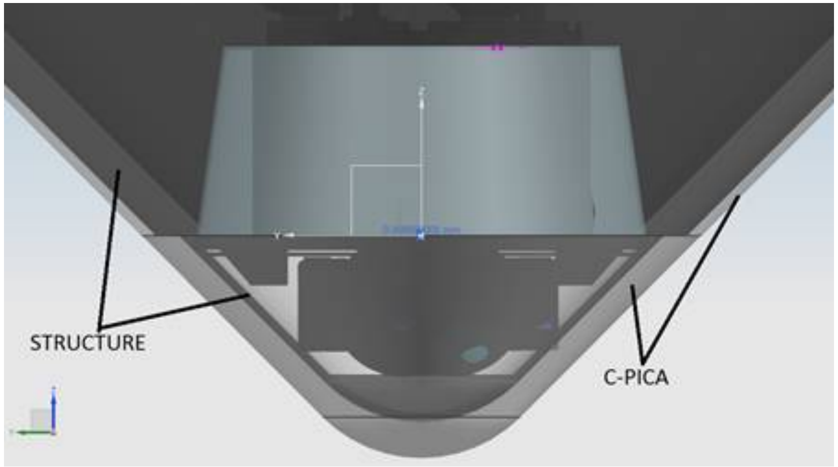
Internal Flight System Configuration



TPS Material Selection

- Available volume in the nose of the spacecraft is important
  - Give space for components to keep the CG forward
  - Give space for the propulsion system to perform the PRM
- Required PICA thickness results in too little space, but C-PICA is much more flexible.
- Rough calculation: Every 1 cm increase in the spacecraft diameter requires ~8 cm increase in the drag skirt diameter to maintain the same beta ratio.
- To remain as compatible as possible with hosts, growing the drag skirt is not desirable, therefore we choose C-PICA.

C-PICA TPS



PICA TPS